IFUP-TH 66/95

STRUCTURE OF POMERON COUPLINGS AND SINGLE-SPIN ASYMMETRY IN DIFFRACTIVE $Q\bar{Q}$ PRODUCTION

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Abstract

Transverse single spin asymmetry in polarized diffractive $Q\bar{Q}$ production is calculated. It is shown that this asymmetry depends strongly on the spin structure of the pomeron coupling, which permits one to study the pomeron couplings properties in future polarized experiments.

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It is known that in high-energy reactions with polarized particles large spin asymmetries are observed. A lots of information on the spin structure of QCD can be obtained from double spin asymmetries [1]; however, it is necessary to have two polarized particle beams (or a polarized beam and a target) to study such asymmetries. For theoretical and experimental investigations of spin effects in QCD, the single spin asymmetry should be very convenient. This problem is very important due to extensive spin programs proposed at HERA, RHIC and LHC (see e.g.[2, 3]).

Single spin asymmetry depends strongly on the hadron properties. It is determined by the relation

$$A = \frac{\sigma(^{\uparrow}) - \sigma(^{\downarrow})}{\sigma(^{\uparrow}) + \sigma(^{\downarrow})} = \frac{\Delta\sigma}{\sigma} \propto \frac{\Im(f_+^* f_-)}{|f_+|^2 + |f_-|^2}, \tag{1}$$

where f_+ and f_- are spin-non-flip and spin-flip amplitudes, respectively. So, single spin asymmetry appears if both f_+ and f_- are nonzero and there is a phase shift between these amplitudes. It can be shown that this asymmetry is of an order of magnitude

$$A \propto \frac{m\alpha_s}{\sqrt{p_t^2}}.$$

Here the mass m can be about the hadron mass [4]. So we can expect large transverse asymmetry for $p_t^2 \simeq$ Few GeV^2. For such momenta transfer the diffractive processes should be important.

The study of diffractive reactions has attracted considerable interest due to the observation of high p_t jets in diffractive collisions [5]. Such processes where a proton is not broken are determined at high energies by the pomeron exchange. It can be interpreted as the observation of partonic structure of a pomeron [6]. These experiments have stimulated theoretical investigations of diffractive reactions and pomeron properties.

The question about the spin structure of the pomeron arises for the diffractive reactions with polarized particles. The experimental study of transverse spin asymmetries in these processes shows that at high energies and momentum transfer $|t| \geq 1GeV^2$ they are not small [7] and can possess a weak energy dependence. This means that the pomeron can be complicated in the spin structure [8, 9].

In this paper we shall calculate the transverse single-spin asymmetry in high-energy diffractive $Q\bar{Q}$ production. It will be shown that this asymmetry depends strongly on the spin structure of pomeron couplings. The obtained effects permit one to study the spin properties of the pomeron from the diffractive reactions in future polarized experiments.

The pomeron is a colour–singlet vacuum t-channel exchange that can be regarded as a two-gluon state. The pomeron contribution to the hadron high energy amplitude can be written as a product of two pomeron vertices $V_\mu^{hh\mathbb{P}}$ multiplied by some function $\mathbb{P}$ of the pomeron. As a result, the quark-proton high-energy amplitude looks as follows

$$T(s,t) = i\mathbb{P}(s,t) V^\mu_{qq\mathbb{P}} \otimes V_\mu^{pp\mathbb{P}}. \tag{2}$$

In the nonperturbative two-gluon exchange model [10] and the BFKL model [11] the pomeron couplings have a simple matrix structure:

$$V^\mu_{hh\mathbb{P}} = \beta_{hh\mathbb{P}} \gamma^\mu, \tag{3}$$

which leads to spin-flip effects decreasing with energy as a power of s. We shall call this form the standard coupling.

However, in some models the spin-flip effects do not vanish as $s \to \infty$ [8, 12]. It was shown that the pomeron–proton vertex is of the form (see [8] e.g.)

$$V^{\mu}_{pp\mathbb{P}}(p,r) = mp_{\mu}A(r) + \gamma_{\mu}B(r), \tag{4}$$

where the amplitudes A and B are connected with the proton wave function. For the spin-average and longitudinal polarization of the proton the term B is predominant. So, the longitudinal double spin asymmetry does not essentially depend on the pomeron-proton vertex structure.

The situation is drastically different for spin asymmetries with a transversely polarized proton. In this case the structure of the pomeron-proton coupling is significant and both the functions, A and B, contribute. Really, in the model [8] the amplitudes A and B have a phase shift. As a result, the single spin asymmetry determined by the pomeron exchange

$$A^{h}_{\perp} \simeq \frac{2m\sqrt{|t|}\Im(AB^{*})}{|B|^{2}} \tag{5}$$

appears. So, the knowledge of all spin structures in the pomeron-proton vertex function is important here. The model [8] predicts that the asymmetry at $|t| \geq 1GeV^{2}$ can be about $10 \div 15\%$.

The form of the quark-pomeron coupling has been studied in ref [13]. It was shown that in addition to the standard pomeron vertex (3) determined by the diagrams where gluons interact with one quark in the hadron [10], the large-distance gluon-loop effects should be important. These contributions are presented in Fig.1. They lead to new structures in the pomeron coupling that is similar, e.g., to the anomalous magnetic momentum of a particle. Really, if we calculate the gluon loop correction of Fig.1a for the standard pomeron vertex (3) and the massless quark, we obtain

$$\gamma_{\alpha}(\not{k}+\not{r})\gamma_{\mu}\not{k}\gamma^{\alpha} \simeq -2[2(\not{k}+\frac{\not{r}}{2})k^{\mu} + i\epsilon^{\mu\alpha\beta\rho}k_{\alpha}r_{\beta}\gamma_{\rho}\gamma_{5}], \tag{6}$$

where k is a quark momentum, r is a momentum transfer. So, in addition to the γ_{μ} term, new structures immediately appear from the loop diagram. The perturbative calculations [13] of graphs, Fig.1, give the following form for this vertex:

$$V^{\mu}_{qq\mathbb{P}}(k,r) = \gamma_{\mu}u_{0} + 2mk_{\mu}u_{1} + 2k_{\mu}\not{k}u_{2} + iu_{3}\epsilon^{\mu\alpha\beta\rho}k_{\alpha}r_{\beta}\gamma_{\rho}\gamma_{5} + imu_{4}\sigma^{\mu\alpha}r_{\alpha}. \tag{7}$$

The spin structure of the quark-pomeron coupling (7) is drastically different from the standard one (3). Really, the terms $u_{1}(r) - u_{4}(r)$ lead to the spin-flip in the quark-pomeron vertex in contrast to the term $u_{0}(r)\gamma_{\mu}$. The functions $u_{1}(r) \div u_{4}(r)$ are proportional to α_{s}. They are not small at large r^{2} [14]. Note that the phenomenological vertex $V^{\mu}_{qq\mathbb{P}}$ with u_{0} and u_{1} terms was proposed in [15].

The new form of the pomeron–quark coupling (7) should modify various spin asymmetries in high–energy diffractive reactions [15, 16]. It has been found from the analysis of

longitudinal double spin asymmetries [16] that the main contribution is determined by the terms u_0 and u_3 in (7). The axial-like term $V^\mu(k,r) \propto u_3(r)\epsilon^{\mu\alpha\beta\rho}k_\alpha r_\beta \gamma_\rho \gamma_5$ is proportional to the momentum transfer r and it survives only in diffractive reactions where the pomeron has a nonzero momentum transfer ($r^2 = |t|$). So, this new $u_3(r)$ term does not change the standard pomeron contribution to the proton structure functions because here the pomeron momentum transfer is equal to zero.

Let us investigate the single transverse spin asymmetry in the $p \uparrow p \to p + Q\bar{Q} + X$ reaction. The standard kinematical variables look as follows

$$s = (p_i + p)^2,\ t = r^2 = (p - p')^2,\ x_p = \frac{p_i(p - p')}{p_i p}, \tag{8}$$

where p_i and p are the initial proton momenta, $r = p - p'$ is the proton momentum transfer and x_p is a fraction of the initial proton momemtum carried off by the pomeron. To be sure that the pomeron gives a contribution, x_p must be rather small. In the case when all the energy of the pomeron goes into $Q\bar{Q}$ production [17] the process is determined by Fig.2. Here the planar diagrams where the pomeron couples with one quark in the loop are shown. There are nonplanar graphs in which gluons from the pomeron interact with different quarks in the loop. Such effects, as a rule, do not exceed 10 percent as compared to the planar–diagram contributions (see e.g. [18]).

In what follows we shall calculate the diffractive $Q\bar{Q}$ production using the form (7) for the pomeron coupling. It leads to higher nonphysical powers $(k_\perp^2)^N$ in traces where $k_\perp$ is a transverse part of the quark momentum in the loop. Such contributions should be cancelled with the nonplanar diagrams that restore the gauge invariance of the total amplitude. However, in the nonplanar propagators the large scalar products $W^2 \sim (kr) \propto x_p s$ should appeared that are determined by the longitudinal component of the pomeron momentum. As a result, we find:

$$\frac{k_\perp^2}{k_\perp^2 + M_Q^2} \to \frac{k_\perp^2}{k_\perp^2 + M_Q^2} - \frac{k_\perp^2}{k_\perp^2 + W^2} = \frac{k_\perp^2}{k_\perp^2 + M_Q^2}\frac{1}{1 + k_\perp^2/W^2};$$

where M_Q is a quark mass. Thus, the nonplanar diagrams should modify the results only for a large transverse momentum $k_\perp^2 \sim W^2 \sim x_p s$.

So, the expression (7) can be regarded as an effective pomeron coupling. The obtained results should be independent of the nonplanar contribution at moderate momenta transfer $k_\perp^2 \leq 5 \div 10 GeV^2$. The complete study of this problem is extremely difficult and will be done later.

The cross sections σ and $\Delta\sigma$ determined in (1) can be written in the form

$$\frac{d\sigma(\Delta\sigma)}{dx_p dt dk_\perp^2} = \{1, A_\perp^h\}\frac{\beta^4 |F_p(t)|^2 \alpha_s}{128\pi s x_p^2}\int_{4k_\perp^2/sx_p}^1 \frac{dy g(y)}{\sqrt{1 - 4k_\perp^2/syx_p}}\frac{N^{\sigma(\Delta\sigma)}(x_p, k_\perp^2, u_i, |t|)}{(k_\perp^2 + M_Q^2)^2}. \tag{9}$$

Here g is the gluon structure function of the proton, $k_\perp$ is a transverse momentum of jets, M_Q is a quark mass, $N^{\sigma(\Delta\sigma)}$ is a trace over the quark loop, β is a pomeron coupling constant, F_p is a pomeron-proton form factor. In (9) the coefficient equal to unity appears in σ and the

transverse hadron asymmetry $A^h_\perp$ in the pomeron-proton vertex determined in (5) appears in $\Delta\sigma$. We calculate the traces using the programme REDUCE and the integrals by the programme MAPLE.

The main contributions to $N^\sigma(N^{\Delta\sigma})$ in the discussed region are determined by u_0 and u_3 structures in (7). They can be written for $x_p = 0$ in the form:

$$N^{\Delta\sigma} = 16(k_\perp^2 + |t|)k_\perp^2 u_0^2 + \Delta N^{\Delta\sigma};$$
$$N^\sigma = 32(k_\perp^2 + |t|)k_\perp^2 u_0^2 + \Delta N^\sigma. \tag{10}$$

where

$$\Delta N^{\Delta\sigma} = 8[(k_\perp^2 + |t|)u_3 - 2u_0](k_\perp^2 + |t|)k_\perp^2|t|u_3;$$
$$\Delta N^\sigma = 16[(k_\perp^4 + 4k_\perp^2|t| + |t|^2)u_3 - 2(2k_\perp^2 + |t|)u_0]k_\perp^2|t|u_3. \tag{11}$$

Note that $u_3 < 0$.

The $k_\perp^2$ dependence of u_i functions which is important in the calculation has been studied. It was found that all functions decrease with growing $k_\perp^2$. A good approximation of this behaviour is

$$u_i(k_\perp, r) = \frac{|t|}{k_\perp^2 + |t|} u_i(0, r), \quad r^2 = |t|. \tag{12}$$

This improves the convergence of the integral over $d^2k_\perp$. The simple form of the $u_0(r)$ function

$$u_0(0, r) = \frac{\mu_0^2}{\mu_0^2 + |t|}$$

was used, with $\mu_0 \sim 1Gev$ introduced in [19]. The perturbative QCD results [14] for the functions $u_1(0, r) \div u_4(0, r)$ at $|t| > 1GeV^2$ have been used.

Both σ and $\Delta\sigma$ have a similar behaviour at small x_p

$$\sigma(\Delta\sigma) \propto \frac{1}{x_p^2}$$

This important property of (9) allows one to study asymmetry at small x_p where the pomeron exchange is predominated because of a high energy in the quark-pomeron system.

We shall calculate integrals (9) using the simple form for the gluon structure function

$$g(y) = \frac{R}{y}(1 - y)^5, \quad R = 3. \tag{13}$$

This form corresponds to the pomeron with $\alpha_{I\!P}(0) = 1$. Just the same approximation for the pomeron exchange has been used in calculations. The analysis can be performed for the pomeron with $\alpha_{I\!P}(0) = 1 + \delta$ ($\delta > 0$) and more complicated gluon structure functions but it does not change the results drastically.

In the diffractive jets production studied here the main contribution is determined by the region where the quarks in the loop are not far of the mass shell. Then the interaction time should be long and the pomeron rescatterings can be important. They change properties of

single pomeron exchange. This type of the pomeron is called usually the "soft pomeron" [20]. It can possess a spin-flip part with the phase different from the spin-non-flip amplitude [8]. So, we can assume that the hadron asymmetry factor in (9) can be determined by the soft pomeron and it coincides with the elastic transverse hadron asymmetry (5). In our further estimations we shall use the magnitude $A^h_\perp = 0.1$.

The calculations were performed for $\beta = 2GeV^{-1}$ [19] and the exponential form of the proton form factor

$$|F_p(t)|^2 = e^{bt} \quad \text{with} \;\; b = 5GeV^2.$$

Our predictions for σ and single spin asymmetry for the energy of the future fixed–target polarized experiments using the proton beam at HERA-(HERA-N) -$\sqrt{s} = 40GeV$, $x_p = 0.05$ and $|t| = 1GeV^2$ for the standard (3) and spin-dependent quark-pomeron vertex (7) are shown in Figs.3, 4 for the light–quark jets. It is easy to see that the shape of asymmetry is different for the standard and spin-dependent pomeron vertex. In the first case it is approximately constant, in the second it depends on $k^2_\perp$, due to the additional $k^2_\perp$ terms which appear in $\Delta N^{\Delta\sigma}$ and ΔN^{σ} in (10) for the pomeron coupling (7).

We calculate the cross sections σ and $\Delta\sigma$ integrated over $k^2_\perp$ of jets, too. The cross sections σ and $\Delta\sigma$ can be written in the form

$$\frac{d\sigma(\Delta\sigma)}{dx_p dt} = \{1, A^h_\perp\} \frac{\beta^4 |F_p(t)|^2 \alpha_s}{128\pi s x_p^2} \, S \; (\Delta S) \tag{14}$$

$$\begin{aligned} S &= 2S_0 + S_1; \\ \Delta S &= S_0 + \Delta S_1, \end{aligned} \tag{15}$$

where S_0 is a contribution of the standard pomeron vertex (3)

$$S_0 \simeq 8[2\ln(\frac{H}{|t|}) + \ln(\frac{|t|}{M_Q^2})] \ln(\frac{|t|}{M_Q^2}) R|t|u_0^2, \tag{16}$$

and $S_1, \Delta S_1$ are determined by u_0 and u_3 terms in the spin-dependent pomeron coupling (7)

$$\begin{aligned} S_1 \simeq \frac{8}{3}[6(\ln(\frac{|t|}{M_Q^2}) + 2)\ln(\frac{H}{|t|})|t|u_3 - 12(\ln(\frac{|t|}{M_Q^2}) + 1)\ln(\frac{H}{|t|})u_0 \\ +3(|t|u_3 - 2u_0)\ln(\frac{|t|}{M_Q^2})^2 + 3\ln(\frac{H}{|t|})^2|t|u_3 + \pi^2|t|u_3]R|t|^2u_3; \\ \Delta S_1 \simeq \frac{S_1}{2} - 16(|t|u_3 - u_0)\ln(\frac{H}{|t|})R|t|^2u_3. \end{aligned} \tag{17}$$

Here $H = sx_p/4$. In (16,17) the parts of S and ΔS determined by the residue R in the gluon structure function (13) are written. In the calculations, a more complicated form of S and ΔS has been used.

Our predictions for σ at the energy $\sqrt{s} = 40GeV$, $x_p = 0.05$ for the standard vertex (3) and spin-dependent quark-pomeron coupling (7) are shown in Fig.5 for light–quark jets.

The obtained $|t|$ -dependence of the cross-section is very similar in both the cases, but σ is larger for the vertex (7).

The asymmetry obtained from these integrated cross sections does not practically depend on the quark-pomeron vertex structure. It can be written in both the cases in the form

$$A1 = \frac{\int dk_\perp^2 \Delta\sigma}{\int dk_\perp^2 \sigma} \simeq 0.5 A_\perp^h \tag{18}$$

As a result, the integrated asymmetry (18) can be used for studying the hadron asymmetry $A_\perp^h$ caused by the pomeron.

Thus, in this paper, the perturbative QCD analysis of single spin asymmetry in diffractive 2-jet production in the pp reaction is performed using the spin-dependent pomeron coupling. The nonplanar graphs eliminated from our consideration can change the $k_\perp^2$ dependence of distributions at large $k_\perp^2$. The obtained results should be true up to $k_\perp^2 \sim 5 \div 10 GeV^2$. The estimated errors in the measured asymmetry [21] show that the structure of the quark-pomeron vertex can be studied from the $k_\perp^2$ distribution of single-spin asymmetry in this momentum–transfer region at HERA-N [2]. Integrated cross sections are determined mainly by the region $k_\perp^2 \leq |t|$. They do not practically depend on the contribution of nonplanar graphs and can be used to extract information on the pomeron-hadron coupling.

The asymmetries discussed here have a weak energy dependence. For the energies of RHIC and LHC fixed–target experiments ($\sqrt{s} = 120 GeV$) they are not far from our results at $\sqrt{s} = 40 GeV$. So, the diffractive polarized experiments at HERA-N, RHIC and LHC energies permit one to study spin properties of quark-pomeron and proton-pomeron vertices determined by QCD at large distances.

I am grateful to A.V.Efremov, P.Kroll, W.-D.Nowak, G.Ramsey, A.Penzo, A.Schäfer, O.V.Teryaev for fruitful discussions. Special thanks to A.Di Giacomo and M.Mintchev Dipartimento di Fisica dell'Università di Pisa, Instituto Nazionale di Fisica Nucleare, Sezione di Pisa, P.Colangelo and D.Nardulli Instituto Nazionale di Fisica Nucleare, Sezione di Bari for critical remarks and hospitality at Pisa and Bari where this paper has been completed.

This work was supported in part by the Russian Foundation for Fundamental Research, Grant 94-02-04616.

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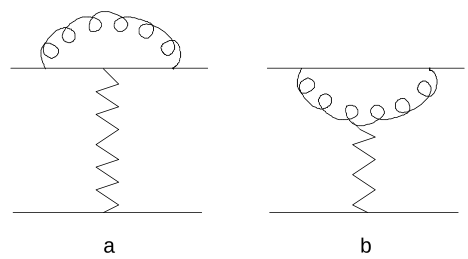

Fig.1 Gluon-loop contribution to the quark-pomeron coupling. Broken line -the pomeron exchange.

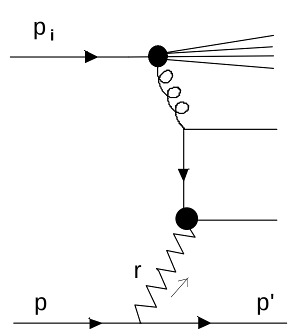

Fig.2: Diffractive $Q\bar{Q}$ production in pp reaction.

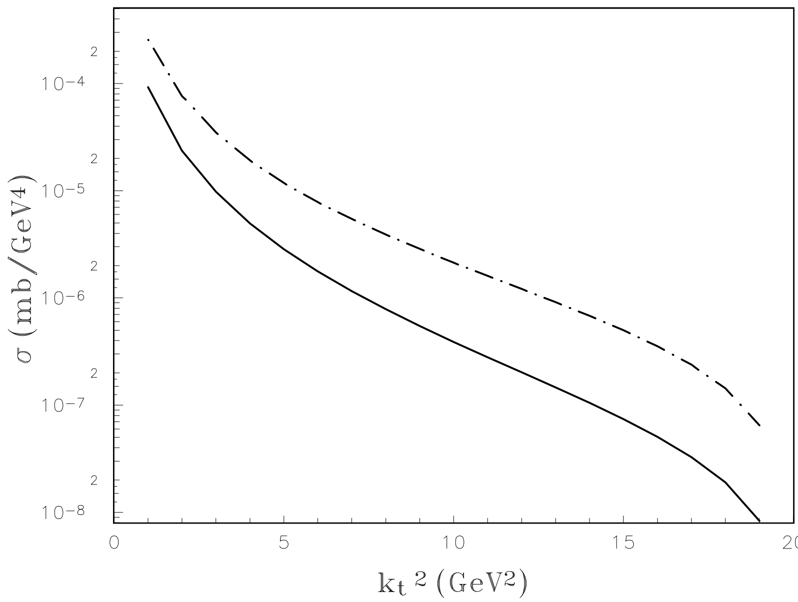

Fig.3 Distribution of σ over jets $k_{\perp}^2$. Solid line -for standard vertex; dot-dashed line -for spin-dependent quark-pomeron vertex.

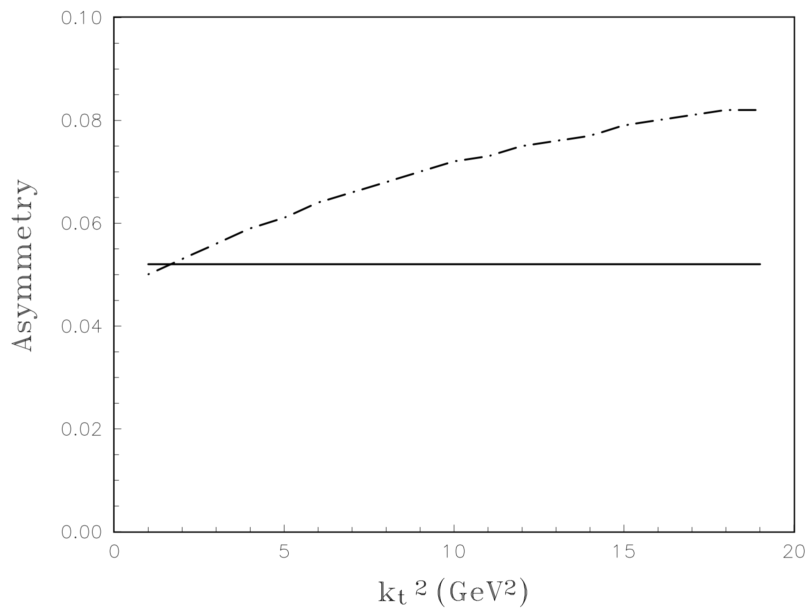

Fig.4: Distribution of asymmetry over jets $k_{\perp}^2$. Solid line -for standard vertex; dot-dashed line -for spin-dependent quark-pomeron vertex.

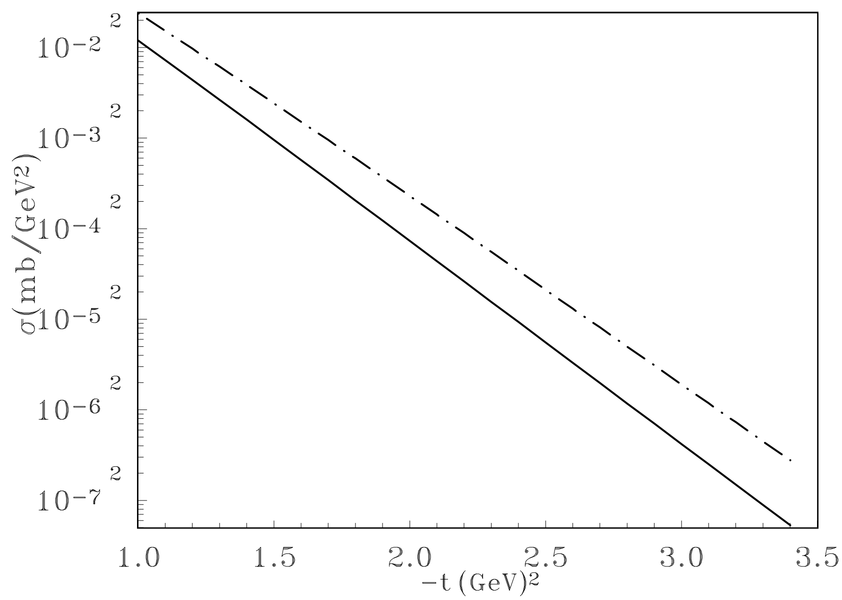

Fig.5 $|t|$– dependence of cross section σ integrated over jet $k_\perp^2$. Solid line -for standard vertex; dot-dashed line -for spin-dependent quark-pomeron vertex.